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N94-25375

**INVESTIGATING PYROLYSIS/INCINERATION AS A METHOD
OF RESOURCE RECOVERY FROM SOLID WASTE**

Final Report
NASA/ASEE Summer Faculty Fellowship Program--1993
Johnson Space Center

Prepared By:	Bobby J. Roberson, Ph.D., Christopher S. LeMay
Academic Rank:	Professor, Student
College and Department:	Bevill State Community College Chemistry Department Fayette, AL 35555
NASA/JSC	
Directorate:	Engineering
Division:	Crew and Thermal Systems
Branch:	Life Support Systems
JSC Colleague:	Charles E. Verostko
Date Submitted:	August 6, 1993
Contract Number:	NGT-44-001-800

ABSTRACT

Pyrolysis/incineration (P/I) is a physicochemical method for the generation of recoverable resources from solid waste materials such as inedible plant biomass (IPB), paper, plastics, cardboard, etc. P/I permits the collection of numerous gases with a minimal amount of solid residue. Pyrolysis, also known as starved air incineration, is usually conducted at relatively high temperatures (> 500 degrees Celsius) in the absence of oxygen. Incineration is conducted at lower temperatures in the presence of oxygen. The primary purpose of this study was to design, construct, and test a model P/I. The system design includes safety requirements for temperature and pressure. The objectives of this study were: 1) to design and construct a P/I system for incorporation with the Hybrid Regenerative Water Recovery System ; 2) to initiate testing of the P/I system; 3) to collect and analyze P/I system data; 4) to consider test variables; and 5) to determine the feasibility of P/I as an effective method of resource recovery. A P/I system for the recovery of reusable resources from solid waste materials was designed, constructed, and tested. Since a large amount of inedible plant biomass (IPB) will be generated in a space-based habitat on the lunar surface and Mars, IPB was the primary waste material tested in the system. Analysis of the effluent gases was performed to determine which gases could be used in a life support system.

INTRODUCTION

Several waste recovery technologies are being considered for use on lunar and Mars habitats. Some of these are biological while others are physicochemical. Others are even hybrids of the preceding types. Results of a NASA Workshop indicate that several waste recovery technologies must be considered and pursued for the development of a human-rated test facility (5). Two systems will then be selected for lunar and Mars Controlled Ecological Life Support Systems (CELSS) applications. Design, construction, and testing of the two prototypes and production of two flight systems should be complete and ready by a target flight date early in the twenty-first century. One of the physicochemical technologies that offers promise for suitable use is pyrolysis/incineration (P/I). Literature reviews and experimentation indicate that a P/I system can be safe, efficient, and practical and might also have Earth-based applications for the conversion of solid waste materials into reuseable resources (4).

One of the major objectives of this study was to compare the processes of combustion and P/I. Recent investigations involving the combustion of IPB reveal that the conversion of IPB to carbon dioxide and water requires about the same amount of oxygen that was produced by photosynthesis. In other words, the amount of oxygen produced during crop growth is equal to the amount required for the oxidation of the biomass produced during plant growth; therefore, the actual amount of oxygen produced that is available for human consumption is in proportion to the amount of biomass actually utilized by humans. The remaining oxygen must be available to oxidize the rest of the biomass back to carbon dioxide and water or the system will not be a regenerative one (2).

Since the IPB is composed of those plant parts that are not used for human consumption such as roots, stems, leaves, etc., these components represent a significant portion of the total plant mass. Specifically, the IPB for lettuce is approximately 10%, 65% for soybeans, and 60% for wheat (2). It is also important to note that not all of the edible plant biomass (EPB) is digestible and will require additional oxidation outside of the humans before it can be recycled back to plant production. A waste model has been developed based upon information from a NASA Workshop (5). Workshop data indicate that the amount of waste generated per person per day in a space-based habitat will be: 1.85 kg of IPB, 0.9264 kg of trash, 0.194 kg of paper, and 0.041 kg of filters. In a space-based CELSS, it is

desirable that the maximum amount of biomass produced be utilized by the crew so that mass, volume, and energy requirements be minimized. Any biomass oxidation process outside of the crew food cycle reduces the overall efficiency of the CELSS in terms of direct crew life support.

Incineration

Incineration is the oxidation of waste using either limited amounts of pure oxygen or oxygen diluted with an inert gas, usually argon or nitrogen, whereas combustion is the complete oxidation of a substance in an excess of oxygen or air. A temperature of 1000 degrees Celsius and a pressure of one atmosphere are preferred. The amount of air present is in 75 to 100% excess (3). The process is relatively fast and results in 97 to 99% reduction of waste materials such as IB, paper, plastics, food and human waste, etc. the excess air, turbulence, and retention time provide conditions for complete combustion. The chemical reaction for the incineration of cellulosic materials is:



Pyrolysis

Pyrolysis is the chemical destruction of a carbonaceous material by heating to 400 to 1000 degrees Celsius in the absence of oxygen, or in a controlled oxygen environment. The process usually results in the formation of four phases of products: a) a gaseous component including hydrogen, methane, carbon monoxide, and carbon dioxide; b) an oil including organic acids, alcohols, ketones, etc.; c) a char including carbon and inert materials; and d) an aqueous phase containing some water-soluble compounds. In general, rapid heating results in higher yields of gases, whereas slower heating results in higher amounts of oils and char (1). The overall reaction for the pyrolysis of cellulosic materials is:



Depending on the temperature of the reaction, the pressure in the chamber, and the amount of air (or oxygen) permitted to enter the chamber, the reaction products will vary in composition.

DISCUSSION

Pyrolysis of IPB and paper revealed that several reusable gases are produced. The process also reduced the mass of solid waste by 97 to 99%. The P/I process was performed in an open system at ambient pressure. It is believed that a combination of high temperature and high pressure might result in a higher degree of decomposition of the waste.

Figure 1 is a schematic of the P/I process.

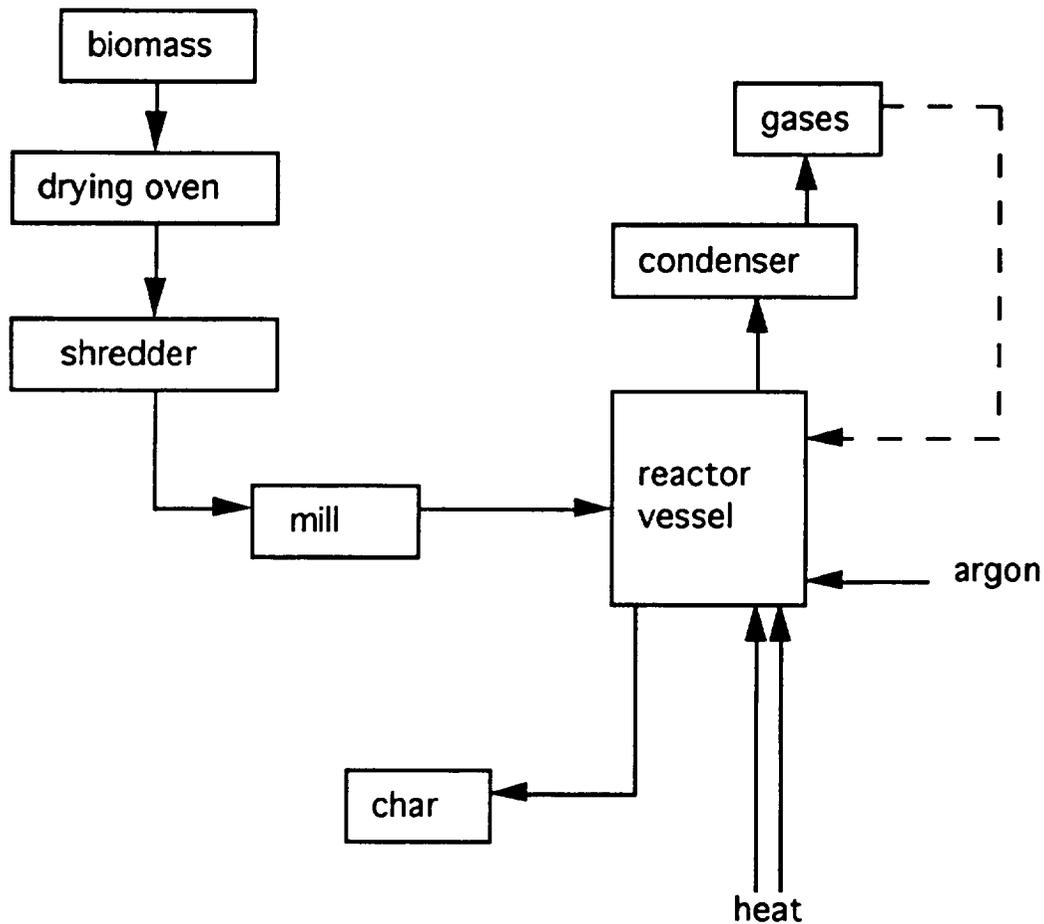


Figure 1.- Schematic of Pyrolysis/Incineration System

A diagram of the pyrolysis reactor system is shown in Figure 2. (This system was constructed by Benjamin P. Fowler, Fowler Engineering Company, Houston, TX.)

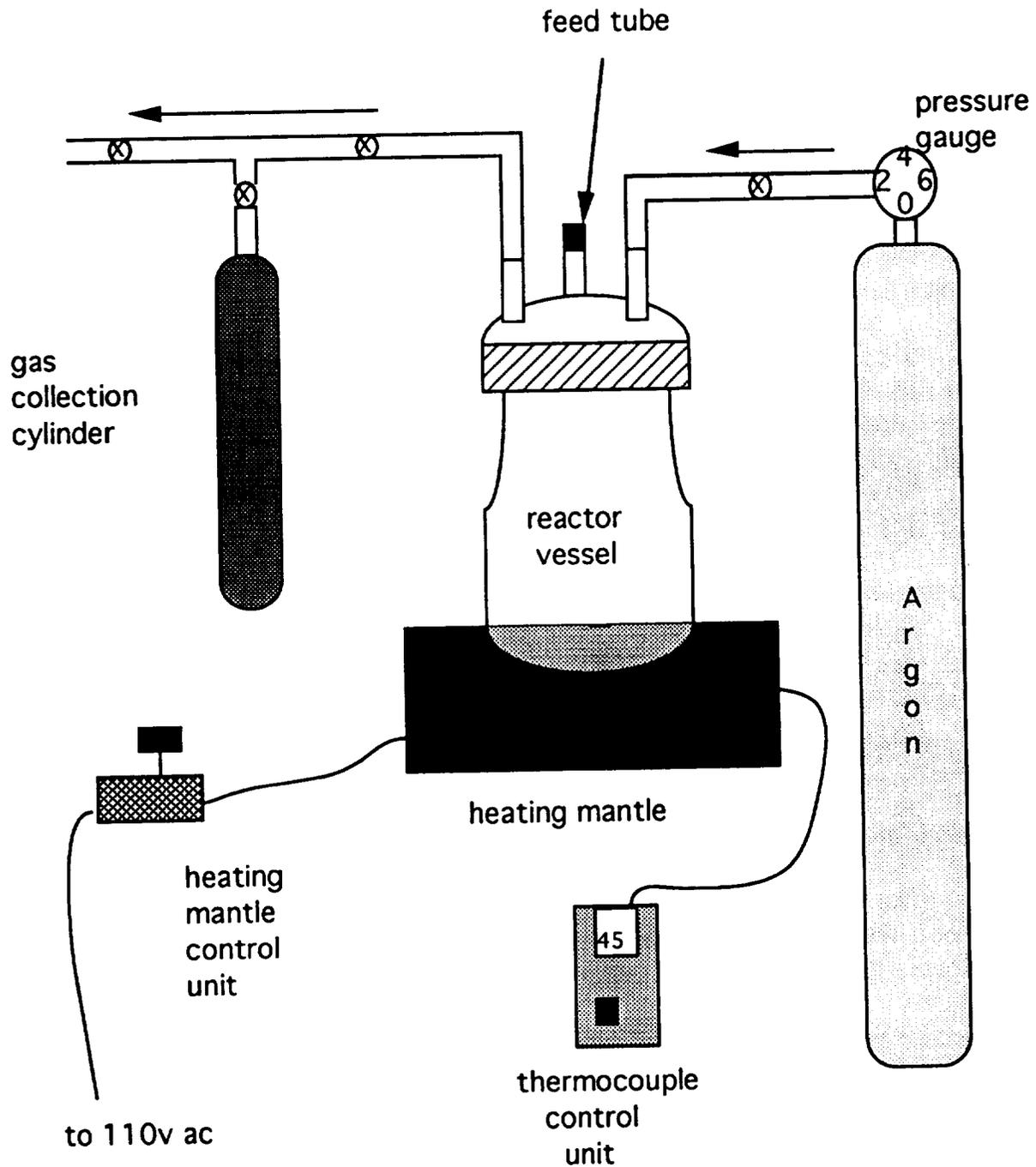


Figure 2.- Diagram of the Pyrolysis System

System Description

The reactor vessel had a volume of 1.35 liters. The base of the reactor vessel was constructed of #314 stainless steel. The base consisted of a 4" weld cap welded to a 4" by 3" reduction section. The reduction section was welded to a 3" by 3" nipple. The head was constructed of #413 stainless steel. It consisted of a 3" weldcap with a 3" threaded coupling. The inlet/ outlet tubes were 1/4" by 4" stainless steel threaded tubes. A GLAS-COL Model # STM 900 heating mantle, a CORD TROL Model # PL-112 heater control unit, and an Atkins K Model # 39658-K thermocouple thermometer were used.

Procedures

Sample Preparation. Samples of IPB (wheat straw and roots) were dried in an oven at 75 degrees Celsius for 48 hours. Samples were shredded and then passed through a 40-mesh screen using a Wiley mill. Samples of paper were cut into 3 mm squares.

Gas Collection. Valves on evacuated, stainless steel, gas collection tubes were opened at specified temperatures and were left open for approximately 5 minutes. After 5 minutes, the valves were closed, and the gas collection tubes were replaced.

Gas Analysis. Gases were analyzed using a Hewlett Packard 5880 Gas Chromatograph and a Hewlett Packard 5987 Gas Chromatograph/Mass Spectrometer.

Residue Collection. After cooling, the reactor vessel was opened. The residue was collected and weighed.

Experimental Results

The experimental results obtained from the pyrolysis of various waste materials are shown in Tables 2 and 3. Table 2 indicates that pyrolysis is very effective in reducing the mass of cellulosic waste material. Table 3 reveals that several short-chain hydrocarbons are produced when cellulosic materials are pyrolyzed. These hydrocarbons have some value as fuels. It is believed that the amount of fuel-grade products might be increased by using a high pressure and high temperature system and by using samples that have large surface areas.

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TABLE 1.- SOLID MASS REDUCTION BY PYROLYSIS*

	SAMPLES	
	wheat, 40-mesh	paper
initial mass (g)	1.005	1.110
final mass (g)	0.073	0.052
% Reduction	92.8	95.3

* Pyrolysis conditions were 767 degrees Celsius for 30 minutes.

TABLE 2.-MAJOR PYROLYSIS PRODUCTS¹ (in ppm)

Gases	Samples		
	Wheat ²	Wheat ³	Paper ³
methane	35.8	40.0	116.0
ethylene	9.0	11.0	23.0
ethane	4.1	6.0	8.0
propylene	8.0	4.0	16.0
propane	33.2	7.0	2.0

¹ Trace components included primarily acetaldehyde and C-3 through C-5 aldehydes and ketones.

² A slow heating process was used (ambient to 767 degrees Celsius in 30 minutes).

³ A rapid heating process was used (ambient to 767 degrees Celsius in 15 minutes).

Specifications for Flight-Ready System

The two most important factors to be considered for a flight-ready system are the use of high temperature and high pressure. A system used in a space-based habitat should also be relatively small and have low power requirements. The system should also be easily maintained. With these objectives and factors in mind, the specifications shown in Table 3 are recommended for a flight-ready system. A suggested design for the reactor vessel is shown in Figure 3. (This system is similar to the Parr high pressure bomb Model 4680 described in the Parr Instrument Catalog, 7th Ed., 1991, pp. 54-55 and 106. The estimated cost of the system is

approximately \$15,000.) The proposed system will be capable of combustion, incineration, and pyrolysis processes.

TABLE 3.- SPECIFICATIONS FOR A FLIGHT-READY PYROLYSIS/INCINERATION SYSTEM

Volume	2000 ml
Sample mass	500 g
Maximum operating temperature	600 degrees Celsius
Maximum operating pressure	4000 psi
Construction material	stainless steel
Feed mode	batch
Heater	Electric element embedded in a shaped ceramic body
Head openings	gas inlet, gas outlet, feed inlet

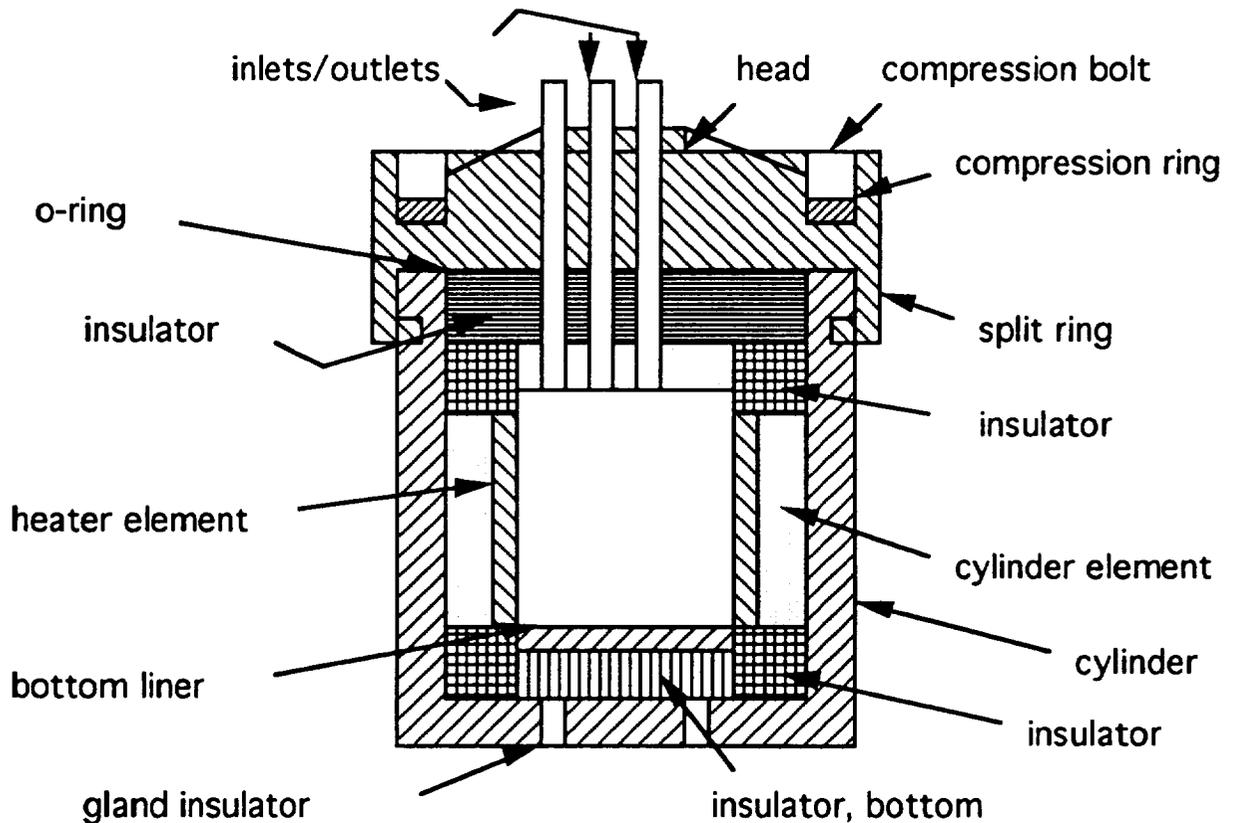


Figure 3.- Diagram of Proposed Pyrolysis Reactor

CONCLUSIONS

The results of this study indicate that pyrolysis/incineration is a physicochemical technology that has practical applications for space-based habitats as well as for waste management and resource recovery on the Earth. An appreciable reduction in the mass of the solid waste plus the recovery of reuseable gases from a variety of waste materials was achieved in a pyrolysis/incineration process. Due to the limited quantities of fuel-grade gases produced, it is believed that these gases should only be used to heat the pyrolysis reactor vessel. The effluent gases contain some particulate matter and numerous trace contaminants such as organic acids, ketones, and aldehydes. These substances should probably be removed if the fuel-grade gases were to be used at remote locations. Any carbon dioxide produced could be used in a plant growth chamber. The major problem with a pyrolysis process is the limited amount of sample that can be treated at high temperature in a closed vessel due to the high pressure generated. Possibly an open system with a continuous injection feed mechanism could offer a solution to this problem.

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